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## The Higgs and Neutralino Sectors of the Next-to-Minimal Supersymmetric Standard Model

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The Next-to-Minimal Supersymmetric Standard Model (NMSSM) includes a Higgs iso-singlet superfield in addition to the two Higgs doublet superfields of the minimal supersymmetric extension. The Higgs sector and neutralino sectors of this model are examined within the context of a future  $e^+e^-$  linear collider.

### 1 Introduction

One of the main tasks for the next generation of colliders will be to determine the mechanism of electroweak symmetry breaking. If this turns out to be the Higgs mechanism together with supersymmetry, it will then become essential to distinguish the minimal supersymmetric model from its non-minimal extensions. In this talk, I will discuss one such extension: the Next-to-Minimal Supersymmetric Standard Model<sup>1,2</sup> (NMSSM) in which an iso-singlet Higgs superfield  $\hat{S}$  is introduced in addition to the two Higgs doublets superfields of minimal supersymmetry,  $\hat{H}_{u,d}$ . Such an extension offers a possible solution of the  $\mu$  problem, generating in a natural way, a value of the order of the electroweak breaking scale  $v$ ; this is achieved by identifying  $\mu$ , apart from the  $\mathcal{O}(1)$  coupling, with the vacuum expectation value of the scalar component  $S$  of the new iso-singlet field.

The superpotential of the NMSSM is given by

$$W = W_Y + \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \frac{1}{3} \kappa \hat{S}^3 \quad (1)$$

where  $W_Y$  denotes the usual MSSM Yukawa components. The first additional term regenerates the  $\mu$ -term of the MSSM when  $S$  gains a vacuum expectation value, while the second provides an explicit breaking of a  $U(1)$  Peccei-Quinn symmetry which would otherwise be present; if not explicitly broken this additional symmetry would lead to a (near) massless pseudoscalar Higgs boson during spontaneous symmetry breaking. The two parameters  $\lambda$  and  $\kappa$  are dimensionless, and are bounded by  $\lambda, \kappa \lesssim 0.7$  at the electroweak scale if they are to remain weakly interacting up to the GUT scale. Also, renormalisation group running favours values of  $\kappa$  lower than  $\lambda$  at the electroweak scale.

## 2 The Higgs Sector

The complex superfield  $\hat{S}$  gives rise to two extra Higgs bosons, one scalar and one pseudoscalar, enlarging the Higgs sector<sup>1</sup> to three neutral scalar fields, two neutral pseudoscalar fields and two charged fields. The Higgs potential will also contain soft supersymmetry breaking terms, parameterized by soft masses and the soft trilinear parameters  $A_\lambda$  and  $A_\kappa$  corresponding to the new terms in the superpotential. The vacuum minimization conditions allow one to replace the soft masses with the electroweak scale  $v = 246$  GeV, and two ratios of vacuum expectation values,  $\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$  and  $\tan\beta_s \equiv \sqrt{2}\langle S \rangle / v$ . It is useful to replace the parameter  $A_\lambda$  with the mass of the heaviest pseudoscalar Higgs  $M_{A_2}$ , in analogy to the usual procedure adopted in the MSSM.

The one-loop Higgs mass spectrum as a function of the heavy pseudoscalar mass  $M_{A_2}$  is shown in Fig.1 (*left*) for a scenario with a low value of  $\kappa$ . The

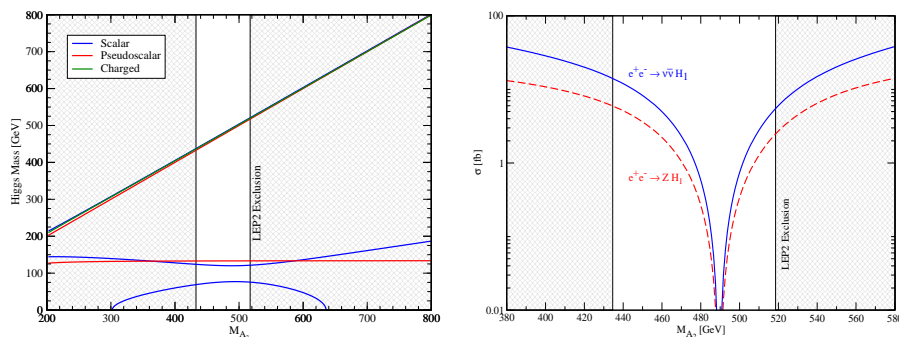


Figure 1: The one-loop Higgs boson masses (*left*) and some tree-level production cross-sections for the lightest Higgs boson at a  $\sqrt{s} = 500$  GeV  $e^+e^-$  linear collider (*right*), as a function of  $M_{A_2}$ , for  $\lambda = 0.3$ ,  $\kappa = 0.1$ ,  $A_\kappa = -100$  GeV,  $\tan\beta = \tan\beta_s = 3$  and a running top mass of  $m_t = 165$  GeV, and maximal mixing.

shaded region is excluded by LEP2, restricting the allowed heavy pseudoscalar mass to values near  $M_{A_2} \approx \mu \tan\beta$ . Notice that rather light Higgs bosons  $\sim 70$  GeV are still not ruled out<sup>3</sup>, due to a reduced coupling of the Higgs boson to gauge bosons which lowers the Higgs-strahlung cross-section. Such a Higgs boson would be very difficult to see at the LHC; its decay is mainly hadronic  $H_1 \rightarrow b\bar{b}$  ( $H_1 \rightarrow \gamma\gamma$  is also suppressed over most of the region) and will be swamped by huge QCD backgrounds. The lightest Higgs boson production cross-sections at a  $\sqrt{s} = 500$  GeV  $e^+e^-$  linear collider are shown in Fig.1 (*right*), where one can see that the coupling to gauge bosons switches

off entirely at  $M_{A_2} \approx 490$  GeV. Although this results in a small range of  $M_{A_1}$  still being inaccessible, these search channels cover most of the allowed parameter space. As the centre-of-mass energy of the collider is increased these cross-sections scale in the usual way.

The Higgs bosons comprised predominantly of the singlet fields increase in mass as  $\kappa$  is increased, with approximate squared masses for the scalar and pseudoscalar given by  $\kappa\langle S \rangle (\kappa\langle S \rangle + A_\kappa)$  and  $-3\kappa\langle S \rangle A_\kappa$  respectively. Once the scalar is heavy enough it may decay  $ZZ^*$  and should be clearly visible at the LHC for values of  $M_{A_2}$  away from the  $Z$  coupling switch-off point.

### 3 The Neutralino Sector

In contrast to the Higgs sector, the neutralino sector<sup>2</sup> is complemented only by the familiar SU(2) and U(1) gaugino mass terms, resulting in a much less complex parameter space. The extra singlet superfield adds an extra higgsino to the spectrum, often called a *singlino*, resulting in five neutralino states. We denote the singlino dominated neutralino  $\tilde{\chi}_5^0$ , with  $\tilde{\chi}_1^0$ – $\tilde{\chi}_4^0$  denoting the other four neutralinos in order of ascending mass. The neutralino spectrum for an example scenario is shown in Fig.2 (*left*) as a function of  $\mu_\lambda \equiv \lambda v/\sqrt{2}$ . In this

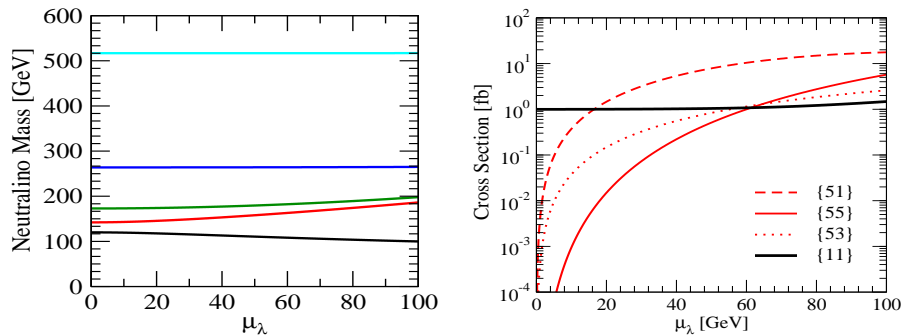


Figure 2: The neutralino mass spectrum (*left*) and the cross-sections for  $e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$  at a  $\sqrt{s} = 500$  GeV  $e^+e^-$  linear collider (*right*), as a function of  $\mu_\lambda$ , for  $\mu_\kappa = 120$  GeV,  $\mu = 170$  GeV,  $\tan \beta = 3$ ,  $M_1 = 250$  GeV and  $M_2 = 500$  GeV.

scenario, the singlino dominated neutralino (*black*) is the lightest neutralino (and the LSP) with a mass of approximately  $\mu_\kappa \equiv 2\kappa\langle S \rangle$ . We have chosen to fix  $\mu$  in this section rather than  $\tan \beta_s$  as previously because of the importance of  $\mu$  to the higgsino spectrum. If the singlino is the LSP (as here) it will be copiously produced at the LHC in squark and gluino cascade decays. A very decoupled state can give rise to macroscopic flight distances for both the

decays  $\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_5^0 l^+ l^-$  and  $\tilde{l}_R \rightarrow \tilde{\chi}_5^0 l$ , but this requires rather low values of  $\lambda$ , with  $\mu_\lambda = 1$  GeV producing a flight distance of order a  $\mu m$  and order a  $nm$  for the two respective decays. Also shown in Fig.2 (*right*) are the cross-sections for  $e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$  at a linear collider, for production of singlino-like ( $\tilde{\chi}_5^0$ ), gaugino-like ( $\tilde{\chi}_1^0$ ) and higgsino-like ( $\tilde{\chi}_3^0$ ) neutralinos. With the anticipated integrated luminosity of  $\int \mathcal{L} = 1 \text{ ab}^{-1}$ , sufficiently large event rates of order  $10^3$  are expected if  $\mu_\lambda$  is not too small.

Comparing the characteristic higgsino mass-scale,  $\mu = \lambda \langle S \rangle$ , with the characteristic singlino mass-scale,  $\mu_\kappa = 2\kappa \langle S \rangle$ , we see that  $\kappa$  does not need to become too large,  $\kappa \gtrsim \lambda/2$ , for  $\tilde{\chi}_5^0$  to become heavier than  $\tilde{\chi}_1^0$ . In this case, the singlino will no longer be the LSP and will decay to  $\tilde{\chi}_1^0$ . Such a neutralino sector would be very difficult to distinguish from that of minimal supersymmetry.

## 4 Conclusions

The NMSSM is a viable extension to minimal supersymmetry, with an in-built solution to the  $\mu$ -problem. In addition to the usual Higgs and neutralino states, it provides an extra scalar and pseudoscalar Higgs field, and an extra neutralino. All of these extra fields increase in mass as  $\kappa$  (the parameter quantifying explicit Peccei-Quinn symmetry breaking) is increased. For small values of  $\kappa$ , the extra scalar Higgs field will be difficult to see at the LHC, while for medium to large values of  $\kappa$ , the extra neutralino will be difficult to identify. Although for much of the allowed parameter space, either the Higgs sector or the neutralino sector will display manifestly non-minimal structure, there is a large part of parameter space where such a non-minimal structure could be hidden. There are also small regions of parameter space where the coupling of the extra scalar to gauge bosons switches off entirely. It will therefore be extremely important to examine the Higgs and neutralino sectors in a precision environment, such as an  $e^+e^-$  linear collider.

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## References

1. D. J. Miller, R. Nevzorov and P. M. Zerwas, Nucl. Phys. B **681** (2004) 3 [arXiv:hep-ph/0304049], and references therein.
2. S. Y. Choi, D. J. Miller and P. M. Zerwas, arXiv:hep-ph/0407209, and references therein.
3. D. J. Miller and S. Moretti, arXiv:hep-ph/0403137.